LHC sensitivity to $h \to \tau^\pm\mu^\mp$

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We study the sensitivity of the LHC, with 20 fb^{-1} of data, to lepton flavour violating Higgs boson decays $h \to \tau^\pm\mu^\mp$ (and $h \to \tau^\pm e^\mp$). We consider the large population of Higgses produced in gluon fusion, combined with leptonic decays of the τ, and estimate that the LHC could set a 95% confidence level bound $BR(h \to \tau^\pm\mu^\mp) < 4.5 \times 10^{-3}$. This correponds to a coupling of order the Cheng-Sher ansatz $y_{\tau\mu} = \sqrt{m_\tau m_\mu/v^2}$.

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A new resonance, hereafter refered to as the Higgs boson (h), was recently discovered [1] around 126 GeV. Its couplings and branching ratios will be determined with additional data; meanwhile, one can speculate on possible departures from Standard Model (SM) expectations. It is known that Beyond-the-Standard-Model (BSM) physics is present in the lepton sector to generate neutrino masses, and should induce Lepton Flavour Violating (LFV) Higgs decays at some rate. We suppose that this rate could be detectable.

The prospects of observing LFV Higgs couplings have been studied in the past, both at colliders [2], and in low energy experiments [3] (see also [4] for supersymmetric models, and [5] for a recent discussion with R-parity violation). The low energy bounds, and their implications for collider searches, were studied in detail for the Two Higgs Doublet Model [6, 7], and for a single Higgs doublet with effective operators [8–11] [29]. They do not exclude observable $h \to \tau^\pm\mu^\mp$ or $h \to \tau^\pm e^\mp$ at the LHC. The bounds that can be set from current $h \to \tau^+\tau^-$ data, and prospects of a dedicated $h \to \tau^\pm\mu^\mp$ search (in the vector boson fusion channel) are discussed in [9].

This brief note advocates searching for $h \to \tau^\pm\mu^\mp$ with Higgses produced in gluon fusion, followed by $\tau \to e\nu\bar{\nu}$. This channel was discussed for heavy Higgs bosons in [13]. Due to the large SM gluon fusion cross section, which we denote as $\sigma_{SM}(pp(gg) \to h) = 19.2 \pm 2.8$ pb, this channel produces more signal events than producing a Higgs in vector boson fusion (VBF), $\sigma_{SM}(VBF) = 1.68 \pm 0.05$ pb. The VBF channel is used for $h \to \tau^+\tau^-$ because the two jets distinguish the signal in the large $(\gamma/Z)^* \to \tau^+\tau^-$ background. However, in the case of $h \to \tau^\pm\mu^\mp$, the hard μ momentum and specific missing energy allow the signal to be sufficiently distinguished from the background that one obtains an interesting sensitivity with current data. Our sensitivity compares favourably with the results of [9], who studied $h \to \tau^\pm\mu^\mp$ following Higgs production in VBF.

We are interested in the lepton flavour violating Higgs decays $h \to \mu^\pm\tau^\mp$, and $h \to e^\pm\tau^\mp$, because we expect the "SM-like" Higgs to couple most strongly to the third generation. We only study $h \to \mu^\pm\tau^\mp \to \mu^\pm e^\mp\nu\bar{\nu}$, because we anticipate that the sensitivity to $h \to e^\pm\tau^\mp \to e^\pm\mu^\mp\nu\bar{\nu}$ should be equivalent, or better. The final state particles $e^\pm\mu^\mp + \not{E}_T$ are the same, so the SM backgrounds should be similar, and the detection prospects for a low p_T muon from tau decay are better than those of a low p_T electron.

The couplings of the SM Higgs are flavour diagonal, so New Physics is required to allow $h \to \tau^\pm\mu^\mp$. For a single doublet Higgs field H, the presence of non-renormalisable operators, for instance of the form $[H^\dagger H][\bar{\ell}_\mu H]\tau_R$, allows flavour-changing couplings for the physical Higgs field h [14]. In the presence of additional scalar fields, such as a 2 Higgs Doublet Model[15], or the NMSSM [16, 17], renormalisable flavour-changing interactions can arise, provided the mass spectrum is away from the decoupling limit [30]. The production rate via gluon fusion could also be modified by New Physics. For instance, in the 2HDM, neglecting the heavy charged Higgses in the loop, it is multiplied by $\sin^2 2(\beta - \alpha)$, where $(\beta - \alpha)$ is the angle between the CP-even mass eigenstate basis and the basis where only one doublet has a vev[31].

There are weak constraints on LFV Higgs decays from low energy data. The limits from processes which the Higgs could mediate at tree level, such as $\tau \to \mu\bar{\mu}\mu$, $\tau \to e\bar{\mu}\mu$ and $\tau \to \eta\mu$, allow $\mathcal{O}(1)$ LFV couplings to the Higgs [6, 8, 9, 19]. More restrictive model-dependent bounds arise from $\tau \to \mu\gamma$ (see *e.g.* [8, 9] for a single Higgs, and [6, 7, 19] for the 2HDM); a LFV Higgs coupling of order the tau yukawa is allowed.

We assume a single "SM-like" Higgs at 126 GeV. In particular, we assume the change in the total decay rate due to New Physics is sufficiently small that the narrow width approximation for production and decay can be used. Most

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of the backgrounds arise from non-Higgs mediated processes, so we study the observable

$$\frac{\sigma(pp(gg) \to h)}{\sigma_{SM}(pp(gg) \to h)} BR(h \to \tau^{\pm}\mu^{\mp}) \tag{1}$$

This circumvents the issue of parametrising New Physics couplings [32]. However, in simulating the backgrounds from Higgs decays, we use the SM production rate $\sigma_{SM}(pp(gg) \to h)$. This is innocuous because the Higgs background is negligeable compared to the dibosons and Z^*s.

Our signal process is $pp(gg) \to h \to \tau^{\pm}\mu^{\mp} \to e^{\pm}\nu\bar{\nu}\mu^{\mp}$, where the Higgs boson is produced by gluon fusion, and was simulated with the Monte Carlo event generator PYTHIA version 8.162 [22]. Other production mechanisms for the Higgs boson were not taken into account, since their rates are at least one order of magnitude lower. The Higgs boson mass was set to 126 GeV.

The background simulations from our previous study [23] of lepton flavour violating Z decays was used to estimate SM backgrounds leading to $e^{\pm}\mu^{\mp}$ dilepton final states. These includes the following processes: $pp \to Z/\gamma^* \to \tau^+\tau^-$, $t\bar{t}$ and tW, and gauge boson (W and Z) pair production. In the background simulations of this new analysis, we also included Higgs boson production via gluon fusion, followed by lepton flavour conserving decays. The SM decays of the Higgs boson leading to $e^{\pm}\mu^{\mp}$ final state are: $pp \to h \to \tau^{\pm}\tau^{\mp}$ where both tau lepton decay leptonically, $pp \to h \to W^+W^-$ where both W decay leptonically, and $pp \to h \to ZZ^*$. Those processes were also simulated using PYTHIA version 8.162 with a Higgs boson mass of 126 GeV.

The simulated signal and SM Higgs boson backgrounds are summarized in Table I (see [23] for similar information on other background processes). The SM cross section of Higgs production by gluon fusion is 19.2 pb for a Higgs boson mass of 126 GV with a total uncertainty of ±14.7 % [24]. Branching ratios from SM were used for $h \to \tau^{\pm}\tau^{\mp}$, $h \to W^+W^-$, and $h \to ZZ^*$ decays; those are 6.73%, 23.3%, and 2.85%, respectively.

Those Monte Carlo events were passed through the DELPHES program [25], with the anti-kt jet reconstruction of FASTJET [26], to simulate the CMS detector response as described in [23].

Processes		$\sigma \times BR$ (pb)	Number of simulated events
SM Higgs back.	$pp(gg) \to h \to \tau^{\pm}\tau^{\mp} \to \ell^{\pm}\nu\bar{\nu}\ell'^{\mp}\nu\bar{\nu}$ with $\ell, \ell' = e, \mu$	0.160	30,000
SM Higgs back.	$pp(gg) \to h \to W^+W^- \to \ell^+\nu\ell'^-\bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$	0.469	100,000
SM Higgs back.	$pp(gg) \to h \to ZZ^* \to f\bar{f}f'\bar{f}'$ with $f = q, \nu, e,\ \mu,\ \tau$	0.548	100,000
Signal	$pp(gg) \to h \to \tau^{\pm}\mu^{\mp} \to e^{\pm}\nu\bar{\nu}\mu^{\mp}$		100,000

TABLE I: Standard Model Higgs boson backgrounds in the search for lepton flavour violating h decay at the LHC (see [23] for similar information about non-Higgs processes); the second column contains $\sigma \times BR$ (in pb) for p-p collisions at $\sqrt{s} = 8\ TeV$ for Higgs boson production via gluon fusion, and the third column shows the number of simulated events in this analysis, which is in all cases greater than 10 times $\mathcal{L}\sigma BR$ with $\mathcal{L} = 20\ fb^{-1}$.

The $h \to \tau^{\pm}\mu^{\mp}$ event selection follows closely what was done in [23] to select $Z \to \tau^{\pm}\mu^{\mp}$ events with an electron and a muon back-to-back in the transverse plane. Events are required to contain at least one muon with p_T greater than 30 GeV and $|\eta| < 2.1$, and at least one electron with p_T greater than 15 GeV and $|\eta| < 2.5$. Events must contain exactly 2 opposite-sign (OS) leptons. Events having one or more reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.5$ are rejected. The azimuthal angle between the muon and the electron, $\Delta\phi(e, \mu)$, has to be higher than 2.7 radians. And the azimuthal angle between the electron and the direction of the missing transverse energy, $\Delta\phi(e, \not{E}_T)$, has to be lower than 0.3.

The final selection criterium has been chosen to exploit the kinematic properties of $h \to \tau^{\pm}\mu^{\mp}$ compared to the remaining SM backgrounds. The τ lepton produced in this Higgs boson decay is higly boosted. Assuming massless particles in the τ-lepton decay $\tau \to e\bar{\nu}\nu$ and using the collinear approximation for these decay products, the τ momentum p_τ can be expressed from the measured electron momentum p_e as

$$p_\tau \ = \ \alpha p_e \quad . \tag{2}$$

The momentum of the two-neutrinos system is then simply $(\alpha - 1)p_e$; and its transverse component should correspond to the missing transverse energy measured in the detector. This α factor can then be related to the Higgs boson mass with the following formula:

$$\alpha \ = \ \frac{M_h^2}{4E_e E_\mu \sin^2(\theta_{e\mu}/2)} \tag{3}$$

using the electron and muon energies E_e and E_μ, and the $\theta_{e\mu}$ angle between the electron and the muon directions. For M_h =126 GeV, α can be used to compare the transverse momentum of the two-neutrinos system, computed under the above hypotheses, to the measured value of transverse missing energy of the event ($\not{E}_T{}^{reco}$):

$$\delta\not{E}_T \;=\; \frac{(\alpha-1)p_T^e - \not{E}_T{}^{reco}}{\not{E}_T{}^{reco}} \tag{4}$$

The distribution of the $\delta\not{E}_T$ variable from Eqn. 4 is shown in Fig. 1a after applying all selection criteria described so far. As expected, the distribution for the signal is peaked at 0 while the backgrounds have lower or higher values, which means that the measured value $\not{E}_T{}^{reco}$ is not compatible with the value of $(\alpha-1)p_T^e$ expected for a Higgs boson of mass of 126 GeV decaying to $\tau^\pm\mu^\mp \to e^\pm\nu\bar{\nu}\mu^\mp$. There are however important overlaps between signal and background for this distribution. Therefore, we also exploit that the transverse momentum of the muon, p_T^μ, is higher in $h \to \tau^\pm\mu^\mp$ events than in SM background events (see Fig. 1b). The 2-dimensional distribution $(\delta\not{E}_T, p_T^\mu)$ is shown in Fig. 2. Events are then required to be in an ellipse centered around the signal distribution and defined as:

$$\left(\frac{p_T^\mu - 60}{25}\right)^2 + \left(\frac{\delta\not{E}_T}{0.25}\right) < 1 \tag{5}$$

(a) (b)

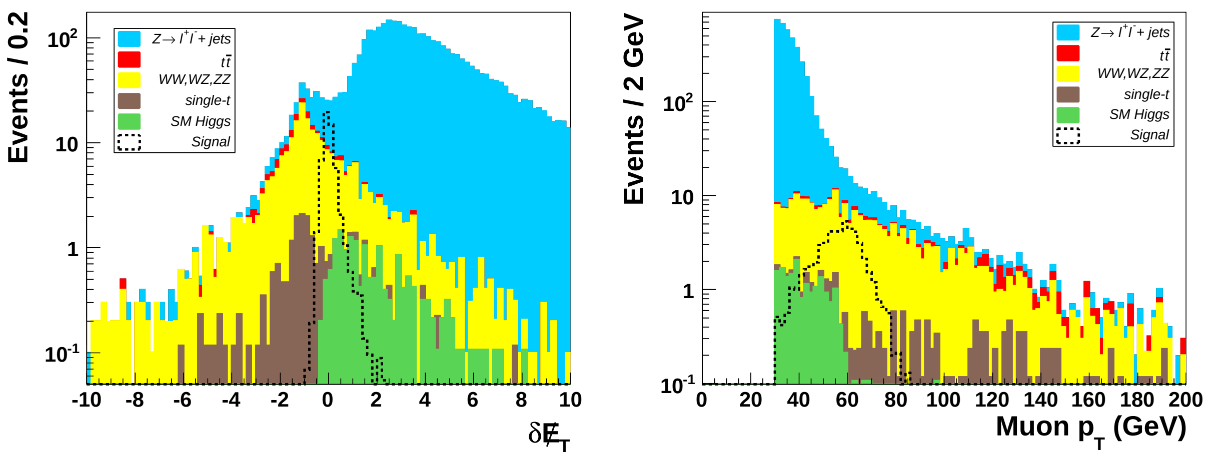

FIG. 1: Distributions of $\delta\not{E}_T$ (a), and of the muon p_T (b), before applying the final selection criterium in the $(\delta\not{E}_T, p_T^\mu)$ plane.

The number of background and signal events at each step of the selection are reported in Tab. II for an integrated luminosity of 20 fb^{-1} at $\sqrt{s}$ = 8 TeV. A good signal to background ratio is achieved, allowing sensitivity to the $h \to \tau^\pm\mu^\mp$ signal with a branching ratio below 1%. In this Table II, contributions from SM Higgs decays, which are included in the total background evaluation, are solely indicated to show how the angular criteria reduce their contribution. At the final stage, LFV Higgs decays largely dominates over SM Higgs decays, whose contribution is almost negligible compared to other SM backgrounds. The number of events selected after applying all selection criteria are reported in Tab. III. The dominant backgrounds are $pp \to Z \to \tau^\pm\tau^\mp$ and diboson pair production (mainly W^+W^-).

The number of events obtained in Tab. III were used to extract a limit on $BR(h \to \tau^\pm\mu^\pm)$. For that purpose, the modified frequentist CL_s [27] method was used. As in our previous study [23], a 3% systematic uncertainty was set on the signal and background yields due to experimental uncertainties on lepton identifications. In addition, we also took into account the 15% systematic uncertainty on Higgs boson production via gluon fusion for the signal and for the backgrounds from SM Higgs decays. The expected 95% C.L. limit calculated with this procedure is:

$$\frac{\sigma(pp(gg)\to h)}{\sigma_{SM}(pp(gg)\to h)} BR(h \to \tau^\pm\mu^\pm) < 4.5 \times 10^{-3} \tag{6}$$

The reach indicated by eqn (6) is phenomenologically interesting. The Cheng-Sher ansätz [28], which can parametrise extra-dimensional models of flavour, gives flavour-changing couplings of order $y_{\tau\mu} \sim \sqrt{m_\tau m_\mu/v^2}$, where

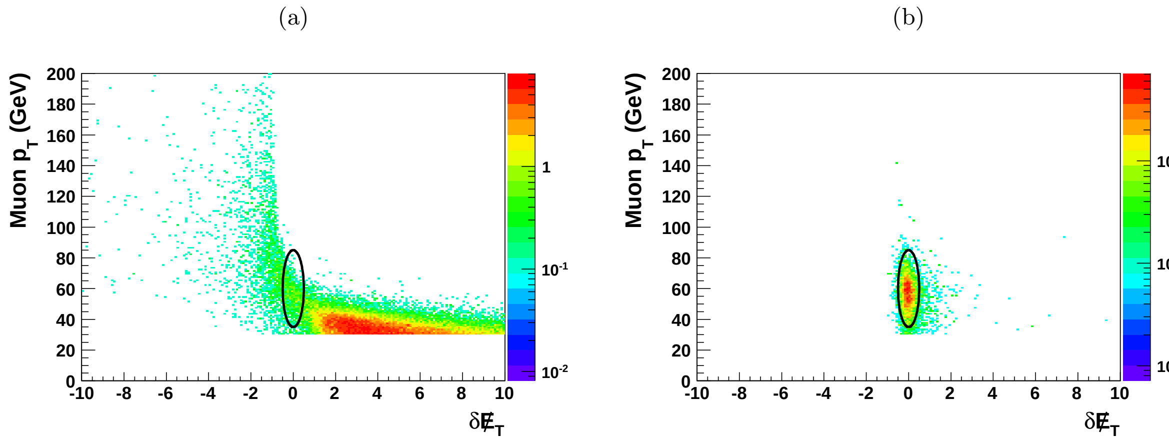

FIG. 2: Event distribution in the $(\delta\not{E}_T, p_T^\mu)$ plane for SM backgrounds (a) and $h \to \tau^\pm\mu^\pm$ signal (b) before applying the final selection criterium in the $(\delta\not{E}_T, p_T^\mu)$ plane, corresponding to the oval. $\delta\not{E}_T$ is defined in eqn (4).

Selection criteria	$N_{backgrd.}$	$N_{h\to\tau\tau}$	$N_{h\to WW}$	$N_{h\to ZZ}$	Signal efficiency (%)	$N_{sig.}$
≥ 1 muon with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.1$ and ≥ 1 electron with $p_T > 15$ GeV and $\lvert\eta\rvert < 2.5$	59271 ± 76	89. ± 3.	235. ± 5.	4.2 ± 0.7	21.2 ± 0.1	145.4 ± 0.9
exactly 2 OS leptons	58447 ± 75	89. ± 3.	235. ± 5.	2.2 ± 0.5	21.2 ± 0.1	145.4 ± 0.9
jet veto: no jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.5$	19477 ± 44	51. ± 2.	123. ± 3.	1.0 ± 0.3	13.1 ± 0.1	89.7 ± 0.7
$\Delta\phi(e,\mu) > 2.7$	13261 ± 36	40. ± 2.	8.7 ± 0.9	0.1 ± 0.1	10.7 ± 0.1	72.9 ± 0.7
$\Delta\phi(e,\not{E}_T) < 0.3$	3885 ± 20	15. ± 1.	2.4 ± 0.5	0.1 ± 0.1	7.85 ± 0.09	53.7 ± 0.6
2D cut in $(\delta\not{E}_T, p_T^\mu)$ plane	53 ± 2	0.6 ± 0.3	0.5 ± 0.2	0	5.34 ± 0.07	36.5 ± 0.5

TABLE II: Selection criteria for the $h \to \tau^\pm\mu^\mp$ search at the $\sqrt{s} = 8$ TeV LHC with $\mathcal{L} = 20\ fb^{-1}$ with the total number of events expected from SM backgrounds, the contribution of SM Higgs decay to the total background, and the signal efficiency (%) and the number of signal events expected for $BR(h \to \tau^\pm\mu^\mp) = 10^{-2}$; uncertainties are statistical only.

$v = 174$ GeV is the Higgs vev. For the h boson, this gives

$$BR(h \to \tau^\pm\mu^\mp) \simeq \frac{m_\mu}{m_\tau} BR(h \to \tau^+\tau^-) \simeq 4.1 \times 10^{-3} \tag{7}$$

where the last number applies when h has the Standard Model branching ratio to taus.

The sensitivity of eqn (6) can be compared to the prospects of $h \to \tau^\pm\mu^\mp$ with Higgs production via VBF (where hadronic and leptonic tau decays could be used), as was studied by Harnik, Kopp, and Zupan [9]. Current data indicate that the production cross sections via gluon fusion and VBF have approximately their SM values, implying more signal events in the channel $pp(gg) \to h \to \tau^\pm\mu^\mp \to e^\pm\mu^\mp + \not{E}_T$. We find a signal efficiency of 5.34 %. Although the results of [9] are presented differently from ours, the gluon fusion channel with leptonic taus, appears to have better sensitivity than VBF with hadronic taus.

Processes	Number of events
Z+jets	34.7 ± 1.9
$t\bar{t}$	1.0 ± 0.3
single-top	0.6 ± 0.3
diboson	14.9 ± 1.2
SM Higgs bkgrd.	1.1 ± 0.3
Total SM backgrounds	52.7 ± 2.3
$h \to \tau^\pm\mu^\mp$ signal	36.5 ± 0.5

TABLE III: After selection criteria of Table II for the $h \to \tau^\pm\mu^\mp$ search at the $\sqrt{s} = 8$ TeV LHC with $\mathcal{L} = 20\ fb^{-1}$, number of events expected for each SM background and for the signal normalized to $\sigma_{SM}(pp(gg) \to h) \times BR(h \to \tau^\pm\mu^\mp)$ with $BR(h \to \tau^\pm\mu^\mp) = 10^{-2}$.

This analysis used missing transverse energy reconstructed from the whole event. However, the $\not{E}_T$ modeling in a fast detector simulation is too optimistic; a full detector simulation including pile-up effects will enlarge $\not{E}_T$ resolution and the overlap between signal and backgrounds, thus reducing slightly the sensitivity. These effects have to be studied by the LHC collaborations in order to perform this analysis. We estimate that the sensitivity is worsened by a factor $\lesssim 2$, if the missing transverse energy is reconstructed solely from the lepton momenta.

The SM Higgs boson is very narrow, mostly decaying to $b\bar{b}$ via a coupling $y_b \simeq 1/35$. Its branching ratios are therefore a sensitive probe of small non-standard Higgs couplings since, away from the peak of the Breit-Wigner, observables lose the $1/y_b^2$ amplification and are suppressed by another small Higgs coupling squared. This is different from the Z boson, many of whose non-standard couplings are better constrained by low energy observables. In this paper we explored the sensitivity of the LHC with 20 fb^{-1} of data to a SM-like Higgs boson decaying to $\tau^{\pm}\mu^{\mp}$ or $\tau^{\pm}e^{\mp}$. We considered Higgs boson production via the largest cross section, which is gluon fusion, and leptonic tau decays, because this gives a clean signature. Assuming experimental systematic uncertainties of 3%, and accurate missing transverse energy reconstruction, we find that the LHC could exclude at 95% C.L. $BR(h \to \tau^{\pm}\mu^{\mp}), BR(h \to \tau^{\pm}e^{\mp}) < 4.5 \times 10^{-3}$.

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[30] For instance, in the 2HDM, two neutral scalars with masses below the decoupling scale, is consistent with low energy constraints including $b \to s\gamma$ [7].

[31] A 2HDM with LFV is of "Type III", so $\tan\beta$ is not uniquely defined [18]. However, if the τ is the heaviest charged lepton, and $\tan\beta_\tau$ in the ratio y_τ/m_τ, where y_τ is the τ Yukawa coupling, then the flavour-changing vertices have a factor $\tan\beta_\tau$. See [7] for a detailed discussion.

[32] see, *e.g.* [20], or [21] for a recent discussion and references.